The Greenhouse Effect

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The distinction is quite striking, as shown in the following figure.
Exercise:
Calculate the radiative equilibrium temperature of the earth’s surface and atmosphere assuming that the atmosphere can be regarded as a thin layer with an absorptivity of 0.1 for solar radiation and 0.8 for terrestrial radiation.
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Assume that the earth’s surface radiates as a blackbody at all wavelengths. Also assume that the net solar irradiance absorbed by the earth-atmosphere system is $F = 241 \text{ W m}^{-2}$. 
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Assume that the earth’s surface radiates as a blackbody at all wavelengths. Also assume that the net solar irradiance absorbed by the earth-atmosphere system is \( F = 241 \text{ W m}^{-2} \).

Explain why the surface temperature computed above is considerably higher than the effective temperature in the absence of an atmosphere.
Solution:
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Since the absorptivity for solar radiation is 0.1, the downward flux of short wave radiation at the surface is \( 0.9 \times F_S \).
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Let $F_E$ be the long wave flux emitted upwards by the surface.
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Let \( F_E \) be the long wave flux emitted upwards by the surface.

Since the absorbtivity for terrestrial radiation is 0.8, there results an upward flux at the top of the atmosphere of \( 0.2 \times F_E \).
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Let $F_L$ be the long wave flux emitted upwards by the atmosphere; this is also the long wave flux emitted \textit{downwards}. 

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Thus, the total downward flux at the surface is $0.9 \times F_S + F_L$. 
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Let \( F_L \) be the long wave flux emitted upwards by the atmosphere; this is also the long wave flux emitted downwards.

Thus, the total downward flux at the surface is \( 0.9 \times F_S + F_L \).

This must equal the upward flux from the surface:

\[
F_E = 0.9 \times F_S + F_L
\]
The upward and downward fluxes at the top of the atmosphere must also be in balance, which gives us the relation

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To find \( F_E \) and \( F_L \), we must solve the system of simultaneous equations

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\begin{align*}
F_L - F_E &= -0.9F_S \\
F_L + 0.2F_E &= F_S
\end{align*}
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This gives the values

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F_E = \frac{1.9}{1.2} \times F_S = 380 \text{ W m}^2 \quad F_L = \frac{0.82}{1.2} \times F_S = 164 \text{ W m}^2
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Then, for the Earth’s surface, we get

\[ \sigma T_{\text{surface}}^4 = F_E = 380 \text{ W m}^2 \]
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Then, for the Earth’s surface, we get

\[ \sigma T_{\text{surface}}^4 = F_E = 380 \text{ W m}^2 \]

Therefore, since \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \), we have

\[
T_{\text{surface}} = \sqrt[4]{\frac{380}{5.67 \times 10^{-8}}} = 286 \text{ K} = +13^\circ \text{C}
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For the atmosphere we have

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\[ T_{\text{atmos}} = \sqrt[4]{\frac{164}{5.67 \times 10^{-8}}} = 245 \text{ K} = -28^\circ \text{C} \]
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\[ T_{\text{atmos}} = 4 \sqrt[4]{\frac{164}{5.67 \times 10^{-8}}} = 245 \text{ K} = -28^\circ \text{C} \]

Note that the surface temperature in this case is some 31°C higher than in the case of exercise 4.6 when there was no atmosphere:

\[ T_{\text{surface}} = +13^\circ \text{C} \]
\[ T_{\text{atmos}} = -28^\circ \text{C} \]
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\[ T_{\text{surface}} = +13^\circ \text{C} \]
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No atmosphere:

\[ T_{\text{surface}} = -18^\circ \text{C} \]
Exercise:
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The layers are in radiative equilibrium with one another and with the surface of the planet.

Show how the surface temperature of the planet is affected by the presence of this atmosphere and describe the radiative equilibrium temperature profile in the atmosphere of the planet.
Solution:
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Begin by considering an atmosphere comprised of a single isothermal layer.
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The effective temperature of the planet now corresponds to the temperature of the atmosphere, which must emit $F$ units radiation to space as a blackbody to balance the $F$ units of incoming solar radiation.
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Since the layer is isothermal, it also emits $F$ units of radiation in the downward radiation.
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Hence, the downward radiation at the surface of the planet is $F$ units of incident solar radiation plus $F$ units of longwave radiation emitted from the atmosphere, a total of $2F$ units,
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Hence, the downward radiation at the surface of the planet is $F$ units of incident solar radiation plus $F$ units of longwave radiation emitted from the atmosphere, a total of $2F$ units, This must be balanced by an upward emission of $2F$ units of longwave radiation from the surface.
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If a second isothermal, opaque layer is added, the flux den-
sity of radiation upon the lower layer will be \(2F\) (\(F\) units of
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If a second isothermal, opaque layer is added, the flux density of radiation upon the lower layer will be $2F$ ($F$ units of solar radiation plus $F$ units of longwave radiation emitted by the upper layer).

To balance the incident radiation, the lower layer must emit $2F$ units of longwave radiation. Since the layer is isothermal, it also emits $2F$ units of radiation in the downward radiation.
and the temperature of the atmosphere is the same as the temperature of the surface of the planet in Exercise 4.6.

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To balance the incident radiation, the lower layer must emit $2F$ units of longwave radiation. Since the layer is isothermal, it also emits $2F$ units of radiation in the downward radiation.

Hence, the downward radiation at the surface of the planet is $F$ units of incident solar radiation plus $2F$ units of longwave radiation emitted from the atmosphere, a total of $3F$ units, which must be balanced by an upward emission of $3F$ units of longwave radiation from the surface.
Radiation balance for a planetary atmosphere that is transparent to solar radiation and consists of two isothermal layers that are opaque to planetary radiation.
By induction, the above reasoning can be extended to an \(N\)-layer atmosphere.
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The emissions from the atmospheric layers, working downward from the top, are $F; 2F; 3F; \ldots; NF$ and the corresponding radiative equilibrium temperatures are 255, 303, 335.... $\left(\frac{F}{N\sigma}\right)^{1/4}\text{K}$. 
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To estimate the corresponding radiative equilibrium lapse rate within the atmosphere we would need to take into account the fact that the geometric thickness of opaque layers decreases rapidly as one descends through the atmosphere owing to the increasing density of the absorbing media with depth.
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Hence, the radiative equilibrium lapse rate steepens with increasing depth.

In effect, radiative transfer becomes less and less efficient at removing the energy absorbed at the surface of the planet due to the increasing blocking effect of the greenhouse gases.
Once the radiative equilibrium lapse rate exceeds the adiabatic lapse rate, convection becomes the primary mode of energy transfer.
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The bottom panel of Fig. 4.5 shows that the wavelength dependence is quite pronounced, with well defined absorption bands identified with specific gaseous constituents, interspersed with windows in which the atmosphere is relatively transparent.
Evaporation

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- In fact, the main process balancing incoming solar radiation at the earth’s surface is evaporation.
- The water evaporated from the ocean is carried upward by convection.
- The moisture reaches levels above the main infra-red absorbers.
- The latent heat is then released by condensation, from where much of it radiates to space.
End of §4.3